DEVELOPMENT OF A NOVEL, LIGHTWEIGHT, PROTECTIVE STRUCTURE TO RESIST IMPULSIVE, DYNAMIC LOADS

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ABSTRACT

This paper discusses the development of a novel, lightweight protective structure and presents results of an analytical and experimental study of its response to explosive loading at a standoff. The paper provides background on the need for lightweight physical protective structures based on the current U.S. military operational paradigm, and briefly discusses the global system objectives and how they were incorporated into Spiral 1.0 of the system (fielded in FY 2008). Lastly, conclusions discuss capabilities and future challenges associated with this type of novel physical protective structure for use in the warfighters' rapidly changing contingency environment.

1. INTRODUCTION

During Operations Enduring Freedom and Iraqi Freedom, a significant threat against U.S. forces and facilities has been direct and indirect fire weapons such as mortars, artillery, shoulder fired rockets, suicide bombings, and small-arms fire. These threats have been faced across the spectrum of operations, and have posed new challenges for close-engagement conditions such as forward operating bases, contingency outposts and outside-the-wire repair and construction operations, where forces are immersed in potential terrorist attack environments. In response to these challenges, the US Army Engineer Research and Development Center (ERDC) has recently completed the FY05 to FY07 Modular Protective System Army Technology Objective (ATO) research program. A major focus of the ATO was development of new lightweight, rapidly deployable protective structures for assets and personnel subjected to these threats.

1.1 Background

Recent advances in protective measures have significantly increased the level of protection for base camp fixed facilities such as administrative offices, command and control centers, dining facilities, and sleeping areas. Utilizing validated approaches for overhead cover, sidewall protection and compartmentalization, the protective posture of these facilities has been significantly enhanced. However, the soldier is also in need of a rapidly deployable and recoverable physical protection system for relatively short-dwell, transient activities in hostile areas. These activities can involve, for example, facilitating repair and construction of roads, bridges, urban facilities, and infrastructure. Conventional protective measures which are most prevalent in theatre—such as earthen revetments and massive concrete walls—impose significant logistical and time constraints, making them unfeasible in these scenarios. As a result, under these transient conditions the warfighter can often be exposed to direct and indirect fire, bombings, and other asymmetric threats, without the capability to quickly deploy and recover protective structures needed to mitigate the encountered threats. The Modular Protective System (MPS) research program was focused on development of a novel protective structure which could be used to fill this protection gap.

1.2 Approach

This paper presents results from an experimental and computational study of the MPS system's dynamic response to blast loading. The experimental component of the study was conducted by exposing an instrumented MPS structure to controlled explosive detonations in order to quantify pressure loading, displacement and structural component strains during the event. Following experimentation, a numerical model was developed (utilizing finite elements with prescribed loading) to simulate the experiments and further analyze system response. Results of the numerical investigation were expected to provide improved insight into system performance, and establish a computational framework for further system development and modification.

2. MPS OVERVIEW

The MPS described in this paper was designed with all of these considerations in mind. A prototype set of modular units were fabricated that consisted of an expandable space frame that can be easily stacked and linked to form adaptable configurations with armor panels that form a continuous vertical face on the sides of the

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units. A parallel ERDC research program was leveraged to produce man-portable ultra high strength concrete armor panels coupled with off-the-shelf composite e-glass panels to provide fragment perforation resistance configurable for a given threat.

3. MPS DESIGN CONSIDERATIONS

Four primary objectives were considered in development of the MPS, which included 1) system modularity, such that protective configurations can be tailored based on encountered conditions, 2) all man-portable components, 3) no equipment required for construction, and 4) threat-based armor configurations, where the amount of armor would be tailored to threats expected in the area. As a result of these objectives, it was expected that the MPS would provide a low-logistics protective capability for warfighters in contingency and urban environments. Based on the requirements for all man-portable components and no equipment to construct, the MPS would minimize logistical footprint associated with fielding and would provide the capability for quickly deploying and recovering a protective structure under short-dwell conditions.

The MPS consists of three basic components. The first component consists of the system support structure, which is formed with lightweight expandable space frames (Figure 1) constructed primarily of pinned tube steel struts and lightweight steel plate members. The frames can be collapsed to minimize transportation requirements and include integrated connections that facilitate the quick linking and stacking of multiple adjacent frames (Figure 2). The frames also include separate channel supports so that armor panels can be slid into place to form a continuous armored surface once the structure is constructed (Figure 3).

Figure 1 Individual expandable MPS space frame

Figure 2 Linking and stacking MPS frames

Figure 3 Completed MPS section with armor panels

The second primary component of the MPS system is a novel ultra high-strength concrete armor panel. Developed through a Cooperative Research and Development Agreement with the United States Gypsum Company as part of the MPS ATO, the concrete panels (named Fortacrete® Armor Panels) consist of a novel blend of sand, cement, pozzolans and fiber reinforcement which yield an unconfined compressive strength of over 20,000 psi. The Fortacrete® Armor Panels are produced at a nominal thickness of 0.5-in., and are laminated with a composite skin to improve durability and performance. In order to achieve the desired protection levels, the concrete armor panels are coupled with the third primary system component, which is an off-the-shelf composite e-glass panel. The e-glass panels consist of woven e-glass fibers in a resin matrix, which provide various protection levels based on panel thickness and material design. An example of the MPS structure faced with Fortacrete® Armor Panels and e-glass is shown in Figure 3.

As a part of the MPS ATO technology transition objectives, at conclusion of the program ERDC worked with the Defense Logistics Agency to establish National Stock Numbers for the system. As a result, NSNs have been established for all system components and for a system kit, which can be ordered through the DLA acquisition process.

With the frames expanded and attached in the desired layout, armor panels are mounted on the front and back sides of the structure in a configuration determined by user objectives. In support of field use, during the research program ERDC developed recommended armor configurations for threats ranging from small-caliber mortars to large-caliber direct fire attack. The armor configurations were identified and validated through an extensive set of laboratory and field experiments, where fragment simulating projectiles, live ammunition and foreign weapons were used to evaluate performance. The resulting recommendations for armor panel use were summarized in a look-up table for quick reference in the field.

Although primary focus of the MPS development was on protection from fragmentation effects and direct fire projectiles, it was recognized that the system must also exhibit enough overturning and flexural resistance to airblast loading that it can fully develop the perforation resistance for larger exploding weapons without toppling due to the dynamic loads. Because the lightweight MPS design results in a relatively low ratio of mass to load collection surface, potential for the system to overturn under airblast loading was specifically studied. Applicability of the system to personnel search areas further necessitated this study, particularly when considering the potential need for resistance to moderately sized explosive charges, such as might be used in a Human Borne IED attack.

4. DYNAMIC RESPONSE EXPERIMENTS

Experimentation presented in this paper focused on the investigation of MPS's susceptibility to overturning from airblast loads produced by bare explosives at a standoff. Because the explosive charges were bare, no casing fragments were generated. These experimental results were used to evaluate the MPS response to blast and to help validate an analytical model as described later.

4.1 Experiment Configuration and Scope

A series of experiments were conducted at Ft Polk, LA to assess the response of the MPS to airblast generated by a range of bare C4 explosive charges at a constant standoff. The configuration for all experiments consisted of an MPS wall with overall dimensions of 15 ft long and 8 ft tall, clad with multiple layers of Fortacrete Armor and e-glass panels. Explosive charges were detonated at a constant height above an 8 ft by 8 ft area covered with steel plate, which was used to minimize debris and dust generation during the experiments. The experiments included the use of high speed video, strain gages, accelerometers, and airblast pressure gages to document the blast event and system response to the loads. A picture of the experimental configuration prior to detonation of the charge is shown in Figure 4.

Figure 4 Typical experiment configuration with explosive charge

4.2 Overview of Experimental Results

As expected, in each experiment overturning motion was noted that increased with explosive charge weight (blast load severity), however, in all cases the system returned to the upright position. Other localized responses were observed in the members and connections, leading to future analysis and design criteria for further system improvements. There were also residual deformations noted in some tube strut members and plate members, but these did not significantly affect response of the system.

For this paper, the analysis and results of only two of the experiments is presented. These two experiments, 1 and 4, represent the smallest and the largest explosive weights used in the series. The experiments not presented, in general, exhibited responses that fall between those given below.

4.3 Experiment 1 Results Overview

Experiment 1 was conducted with the smallest explosive charge in the experimental series. Post-test results indicated that global response of the system was minimal, with only 1 in. to 2 in. of residual global translation (displacement away from charge) and very little rotation observed. Because of the system design, which provides for large amounts of rotational and translational displacement between structural components

without structural damage, a moderate amount of internal displacement was observed even though global response was small. Excessive local displacement in one of the armor support channels allowed several of the concrete and e-glass panels to fall out on the front face, but due to their durability no damage was observed. The blast loading did not result in any material ejected to the back of the structure, indicating little danger from blast-induced ejecta on the protected side.

4.4 Experiment 4 Results Overview

To investigate the upper limit of dynamic response, Experiment 4 was conducted with the largest explosive charge in the series. In this experiment, the charge weight was three times larger than that used in Experiment 1. Prior to Experiment 4, damage to the structure incurred in Experiments 1 through 3 was repaired. Furthermore, because of continued observation of excessive displacement in certain armor support channels, blocking was added to as a temporary means to prevent the channel failures and allow for observation of other structural response modes.

Post-test results indicated that the wall experienced significant global translation and rotation, but remained stable and did not topple in response to the impulsive loading. The greatest residual global translation occurred at the wall ends, with 6-in. to 8-in. of displacement (away from the charge) measured at the front face. Significantly less residual displacement was observed near the wall center, ranging between approximately 1.5-inches and 3-inches (away from the charge). Residual global translation measurements taken at the wall's back face were less, with only 2.5-in. measured at the wall ends and 1-in. to 3-in. measured near the wall center. This indicates that as a result of internal displacement, the structural frame began to close, reducing the wall's overall footprint width. High speed video documentation indicated significant global rotation of the wall (approximately 10 deg maximum rotation) as well as significant internal displacements between structural components. As with the prior experiments, primary permanent damage to the system occurred in the armor support channels, even with the blocking which was placed to reduce this effect. As a result of the support channel damage, two front-face armor panels near the wall center fell out. However, no debris was ejected from the back face, indicating little danger from blast-induced ejecta on the protected side.

5. LS-DYNA FINITE ELEMENT ANALYSIS

In addition to experimental results, ERDC developed a highly detailed finite element model for assessing response of the MPS to airblast loading using the LS-DYNA finite element software running on high performance computers at ERDCs' Major Shared Resource Center (MSRC). The primary purpose of this model was to investigate the load absorption characteristics of the MPS system, its ability to redistribute highly transient loads and strains, uncover potential structural weaknesses, and assess the overturning tendencies of the MPS to airblast loads.

5.1 LS-DYNA and Computational Overview

LS-DYNA is a commercial version of DYNA3D developed by Livermore Software Technology Corporation. LS-DYNA is a general purpose explicit and implicit finite element program for modeling highly dynamic and transient problems involving large deformations and non-linear response. LS-DYNA features include a large library of constitutive models and element types as well as sophisticated automatic contact surface modeling and solvers such as Arbitrary Lagrangian Eulerian (ALE) and coupled fluid-structure interfaces that are applicable to the problems addressed in this paper. The analyses described in this paper were conducted using LS-DYNA version 971 running on a Cray XT3 (Sapphire) at the ERDC MSRC. Sapphire contains 4,096 compute nodes each with a 2.6 GHz Opteron 64-bit dual-core processor and dedicated memory. Sapphire is rated at 42.6 TFLOPS peak computational performance.

5.2 LS-DYNA MPS Model Description

The MPS is capable of absorbing and redistributing loads and deformations due to the pinned strut connections, integrated cables and straps, and linkages to adjacent units. In order to capture this type of behavior in the finite element model it was necessary to explicitly model nearly all the parts and connections. When possible some details were modeled in a simpler fashion, without compromising the overall response of the

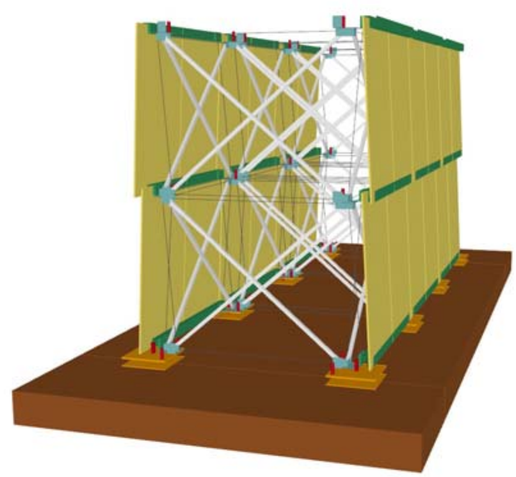

Figure 5 LS-DYNA finite element model of the MPS

model. All steel parts were modeled using Material Type 3, Plastic Kinematic using properties of A513, A1011, A108, and mild carbon steel as appropriate.

The LS-DYNA model included all six MPS units as configured in experiments, three units across and stacked two high (Figure 5). Because it was important for modeling load redistribution and energy loss as accurately as possible, the MPS top and bottom plate members, alignment pins, channel members, armor panels and struts were explicitly modeled in detail using shell elements for the tubes and plates, thick shell elements for the armor panels, and beam elements for the pins. Automatic general contact surfaces with static and kinetic friction were generated between each part. The automatic general contact surfaces allowed the individual model parts to slide with friction, separate, and impact in a realistic manner without having to predetermine what parts will come in contact with each other during the analysis. The slotted pin connections were modeled more simply by explicit beam elements that allowed limited relative movement between adjacent units under loading similar to the actual MPS design.

The MPS design includes straps that can be tightened after the units are in place to help provide some additional clamping forces between the upper and lower units and between the support channels and the armor panels. These straps were modeled explicitly in the LS-DYNA model using Material Type 71, Cable Discrete Beam elements that were initialized with an appropriate tensile force. These cable models do not support compressive forces so during a dynamic analysis the cables can go slack when necessary to realistically model strap behavior. In addition, because gravity is an important force in resisting overturning motion for the MPS, the LS-DYNA model was initialized with gravity forces applied. Dynamic relaxation was employed to distribute the cable and gravity loads and achieve equilibrium prior to application of the dynamic airblast loads.

Because the flexural capacity of the armor panels in the experiments was not challenged by the airblast loading and the panels had no residual damage, in the LS-DYNA model the panels were modeled with Material Type 3, Plastic Kinematic, with concrete properties based on laboratory tests of the Fortacrete® Armor Panels. Modeling the flexural response of the panels and how the panels transferred airblast loads to the frame were an important aspect of the overall model design.

The soil material model was Material Type 5, Soil and Crushable Foam using properties of a typical dry, sandy clay.

The LS-DYNA MPS model consisted of 200 individual parts, over 417,000 nodes, 92,000 solid elements, 269,000 shell elements, 12,672 thick shell elements, and 4,500 discrete beam elements. Running 128 cpu's on Sapphire, a typical analysis required 20 to 48 hours of clock time and 2500 to 6100 hours of cpu time. Approximately 95,000 cpu hours were expended developing, testing and running this model.

5.3 LS-DYNA MPS Model Airblast Loads

Early in the LS-DYNA modeling process it became evident that the MPS as configured in the experiments was benefited by the negative phase of the airblast loading and the unloading produced by edge effects at the top and sides of the configuration. This in effect helped arrest the overturning motion of the units allowing the units to return to the upright position at late time. In addition, as the airblast wrapped around the units and began to act on the back faces of the units additional forces acted on the units to help arrest the overturning motion.

Because Experiment 1 did not include pressure measurements, the loading on the LS-DYNA model of this experiment was estimated using the software ConWep. ConWep can include edge effects in the pressure load estimates, but it does not include negative phase estimates. The negative phase was calculated and appended to the ConWep loads using procedures in Army TM-855. The ConWep loads were calculated based on the range from the detonation to the center of each armor panel. The loads were applied uniformly across each individual front side armor panel facing the charge and on each rear side armor panel facing away from the charge. Loads were also applied uniformly to the front and back side armor support channels in a similar manner. No loads were applied to the tube struts or between the front and back panel.

For Experiment 4, the actual pressure time histories from the airblast pressure gages on the front and back faces of the MPS units were used to construct appropriate loads for the LS-DYNA model. Loads were applied in the same manner as for Experiment 1.

5.4 Comparison of LS-DYNA and Experiment 1 Results

Comparison of the model response to the experimental MPS response was very good overall. As mentioned above, it was evident from the experiments and the LS-DYNA analyses that the MPS as configured in the experiments was assisted in overturning resistance by the negative phase of the loading, edge effects, and back face loading. In the LS-DYNA model, if the negative phase of the loading was not applied the overturning motion was much higher than in the experiment and had not reached maximum rotation at 300 msec. In addition, the tendency for the topmost armor support channels to

rotate upon applied load was evident in both the model and in Experiment 1. This resulted in one set of front armor panels falling from the upper unit in the experiment and all front panels falling from the upper units in the LS-DYNA model. This was a late-time occurrence, however, long after any weapon fragments would have impacted and been stopped by the panels in an actual event. Even so, the experiment and the model agree that a simple design change may be necessary to prevent rotation of the topmost channels and loss of grip on the upper panels.

Strain gages were applied at a location halfway between the center pin and the upper end pin on several tube strut members in Experiment 1. Four strain gages were applied at each location, one on each of the tube strut faces, to measure combined pure axial and flexural strain. In all strain plots the strain is in the direction of the longitudinal axis of the member. In general, the LS-DYNA model agreed with the measured strains in both level and nature. The predominant strains were elastic and flexural in nature, and changed in sign cyclically as a function of the dynamic flexural response. Generally, the highest flexural response was perpendicular to the plane containing each tube strut pair.

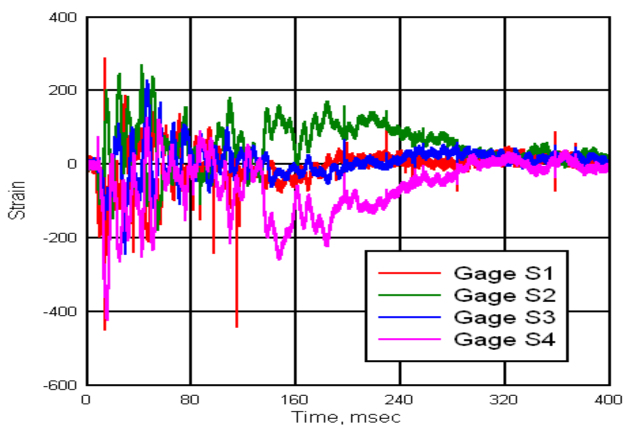

Figure 6 Experiment 1 strain gage data from S1, S2, S3 and S4

Figure 6 shows the strain data from gages S1, S2, S3, S4 and Figure 7 shows the strain data from gages S5, S6, and S8 from Experiment 1. The character of the strain in the tube strut members at various time intervals can be compared to visual cues from the high speed video. From 4 to 8 msec the shock from the airblast positive phase passes through the struts primarily as an axial wave in Figure 6 (all four strain gages initially go into compressive axial strain because the strut was in a plane perpendicular to the front armor panels). In Figure 7 the initial shock produces flexural strains (gages S6 and S8, on opposite faces of a strut parallel with the front armor panels, register strains of opposite sign). From 8 to 60 msec the tube strut flexes cyclically as the overturning motion of the units begins. It can be seen when zoomed into this area of the plot that the flexure during this phase alternates from one transverse axis to the other in Figure 6 and primarily about one transverse axis in Figure 7. The effect of the negative phase of the loading, which acted on

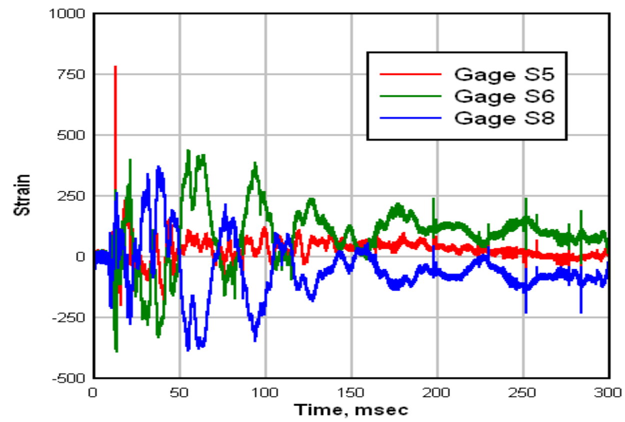

Figure 7 Experiment 1 strain gage data from S5, S6 and S8

the units from 8 to 50 msec, temporarily arrests the overturning motion. This effect appears at the strain gages at approximately 130 to 140 msec, resulting in significant damping of most of the tube strut flexural motion, locking it in flexure temporarily about one transverse axis, with a gradual decrease in flexural strain as the units slow to peak overturning displacement at about 300 msec. After 300 msec, as the units begin to return to the upright position under gravity loading and rebound, the tube strut strain is nearly zero. For brevity, the plots for the remaining gage locations are not shown, but they too show similar behavior of predominantly cyclically elastic flexural response.

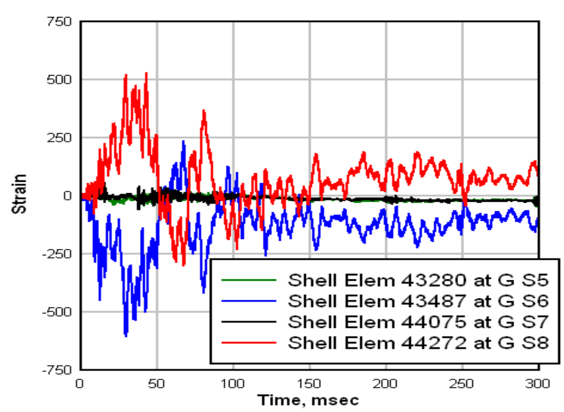

Figure 8 LS-DYNA strains for S5, S6, S7 and S8

Figure 8 shows the composite LS-DYNA strain gage predictions for gages S5, S6, and S8. Figures 9 and 10 show individual comparisons of LS-DYNA strain results at the S6 and S8 gage locations. The LS-DYNA model compared very well with the experimental measurements in magnitude, phase, and character at the locations shown and at most other strain gage locations indicating the

model was able to replicate very well the load distribution and energy absorption characteristics of the experimental results.

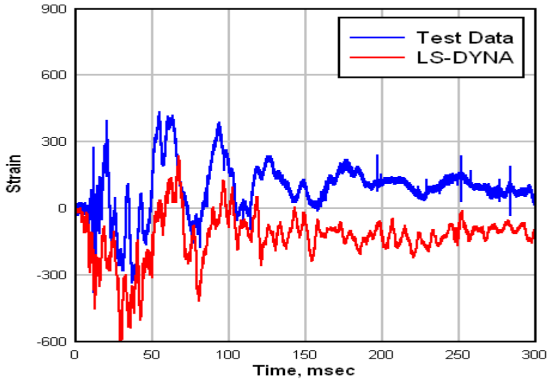

Figure 9 Experiment 1 and LS-DYNA strains for S6

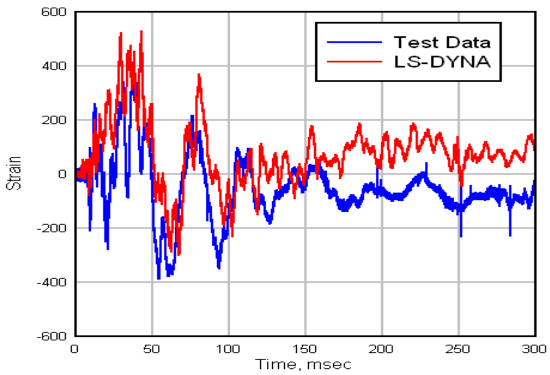

Figure 10 Experiment 1 and LS-DYNA strains for S8

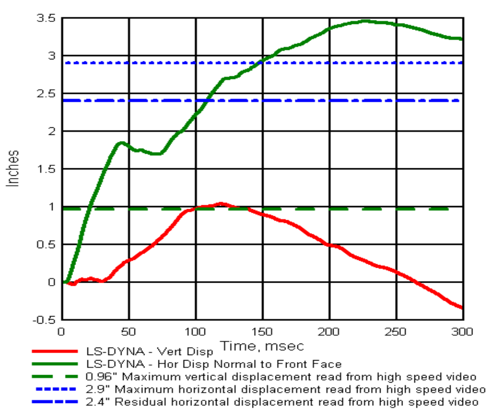

Figure 11 Experimental and LS-DYNA displacements at the top front center edge of the units

The LS-DYNA model was only run to 300 msec for Experiment 1, at which point the maximum displacements had been reached and the model had returned upright after undergoing some overturning displacement. Figure 11 shows a comparison with LS-DYNA horizontal and vertical displacements at the top front center edge of the units. Figure 11 indicates the LS-DYNA model had a very fast initial horizontal displacement of less than 2 inches upon onset of the airblast loading, followed about 25 msec later with a slower vertical displacement as overturning motion begins. High speed video of the event was used to estimate the magnitude and timing of the MPS displacements at the same location. The maximum and residual horizontal and vertical displacements are indicated by the horizontal lines in Figure 11. The LS-DYNA model did very well compared to the experimental displacements, especially the vertical displacement of approximately 1 inch, and the time of the peak LS-DYNA model displacements also agreed with the high speed video. In the horizontal displacement curve in Figure 11 the dip that occurs between 40 and 70 msec is the effect of the negative phase helping to mitigate the overturning motion in the LS-DYNA model. This sudden but temporary reversal in displacement is also easily visible in the high speed video at the same location in time. Momentum imparted to the MPS is not entirely reduced, however, as seen by the slower rise to peak after 70 msec, which was also seen in the high speed video.

5.5 Comparison of LS-DYNA and Experiment 4 Results

In Experiment 4, the explosive standoff was held constant, but the explosive weight was increased by a factor of 3. As in Experiment 1, panels at the top center wall location fell at late time due to channel rotation. Pressure gages at various locations on the front and back panels recorded airblast pressures that were used to drive the LS-DYNA model. No strains were measured but an attempt to capture the motion of the MPS units was made using an array of accelerometers at various locations. It was determined after examining the accelerometer records, however, that the accelerometers did not reliably capture both the early time shock with peaks on the order of 1,000 to 10,000 g's and the late time accelerations which were well less than an order of magnitude lower and below the range of gage sensitivity. At the point that accelerations dropped below sensitivity of the accelerometers the horizontal displacement was only approximately 20% of its eventual late-time peak and the vertical displacement was just starting.

However, the high speed video provides enough information regarding the relatively slow overturning motion in Experiment 4 that several comparisons can be made to assess the accuracy of the LS-DYNA model. The motion of the front top plate of the upper unit (shown by arrow in Figure 12) is visible up to peak displacement and at late time after the MPS units have returned to the upright position. The maximum horizontal displacement of this point, estimated from the high speed video, is 24 inches compared to the LS-DYNA model which had a maximum displacement of 16.2 inches. The maximum vertical displacement at this point, estimated from the high speed video, was 8 inches compared to an LS-

DYNA model displacement of 2.9 inches. It is believed that the lower displacements in the model can be attributed to the response of the leveling plates on the back side in the model, which penetrated significantly into the soil absorbing some of the energy contributing to higher displacements.

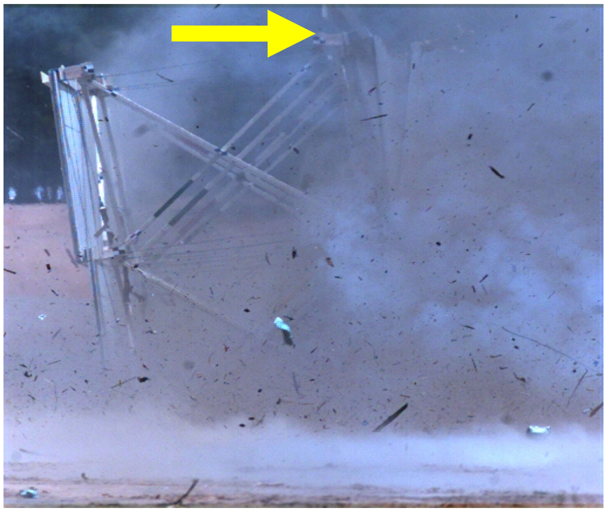

Figure 12 High speed video capture from Experiment 4

The residual displacement of the back leveling plates in the LS-DYNA model was downward 4.3 inches, penetrating the soil. From the high speed video the residual vertical displacement at this point in the test article was approximately 0.0 inches. The soil model used in the LS-DYNA analyses did well for the lower loadings in Experiment 1, but proved too compressible for the increased loads in Experiment 4. The compressibility noted in the soil model was more likely due to the simpler Soil and Crushable Foam model in LS-DYNA rather than the assumed soil properties. In future analyses a more robust soil model will be employed to better model the soil-structure interaction. However, it should be noted that while the LS-DYNA model for Experiment 4 did not exactly match the estimated experimental displacements, the LS-DYNA model gives an indication of probable response of the MPS on soft soil subjected to the same loading.

CONCLUSIONS

MPS development was focused on the objective of providing warfighters with a lightweight, threat-tailored protective structure that can be rapidly deployed and recovered in user-defined configurations. Successful development of such a system was expected to provide the Army with a physical protection capability that could not be met with common protective structures such as earthen revetments and large concrete barriers. Through extensive development and validation research efforts, the MPS has been shown to achieve the required objectives and provide the warfighter with a new force protection capability for protection from direct and indirect fire attack. At the current time MPS systems have been fielded with forces operating in Iraq, and requests have been made for further material acquisition.

With regard to the lightweight system's response to dynamic, impulsive loading, in the configuration tested it displayed exceptional overturning resistance to the applied airblast loads. Although a typical installation might employ a longer line of units or a closed configuration, it is believed that these configurations would provide even more resistance to overturning through linking to adjacent units and the inherent stiffness corners provide.

The LS-DYNA model proved to accurately reproduce the capacity the MPS has to resist overturning under application of dynamic, impulsive loading as seen in the experiments. Furthermore, comparison of strains in the model tube strut members with gage data from Experiment 1 indicates that the model accurately absorbs and distributes the highly transient dynamic loads throughout the framework. The quality of this response was a result of the effort put into modeling the detailed pinned connections, cables, straps, pretest loads, and contact surfaces. Finally, the ability of the model to reproduce details such as rotation of the upper armor support channels and loss of grip on the upper armor panels as seen in the experiments demonstrates the LS-DYNA model successfully provides accurate insight into the response of the MPS to airblast loading and will be a useful tool for further studies.

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